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Spatial variability of switchgrass (*Panicum virgatum* L.) yield as related to soil parameters in a small field

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Abstract

The harvested biomass of switchgrass (*Panicum virgatum* L.) is generally much lower than its potential; this may be due to several factors including not recovering all the biomass at harvest, weed competition, pests, disease and spatial variation of soil features. The objective of this research was to quantify the yield spatial variation of switchgrass and relate it to soil parameters, in a field of about 5 ha, in 2004 and 2005. Several thematic maps of soil parameters and biomass yield were produced using GIS and geostatistical methods. Soil parameters changed consistently within very short distances and biomass yield varied from 3 to more than 20 Mg ha^{-1}. This remarkable variation indicates that the potential for increasing switchgrass productivity is a real prospect. Furthermore, spatial variation of yield showed similar patterns in the two years (r = 0.38**), and therefore a major influence of site characteristics on switchgrass yield can be assumed to occur. Significant correlations were found between biomass yield and soil N, P, moisture and pH as well as between soil parameters. Some soil parameters such as sand content showed patchy spatial distribution. Conversely, a reliable spatial dependence could not be identified for other parameters such as P. Further research is needed.

Key words: Biomass; Geostatistics; Soil parameters; Spatial Variation; Switchgrass.

Abbreviations: Y04 and Y05 = biomass yield in 2004 and 2005; SS = soil strength; SM = soil moisture; SC = sand content; SiC = silt content; CC = clay content; OM = soil organic matter; P = available phosphate; N = total Kjeldhal nitrogen.

1. Introduction

Switchgrass (*Panicum virgatum* L.) is a warm-season perennial C_4 grass native to North-America. Thanks to its high potential yield and low input requirements switchgrass has recently attracted the interest of researchers for thermo-chemical or ethanol end uses (McLaughlin et al., 2002; Samson and Omelian, 1992). The introduction of switchgrass into the conventional cropping systems will mostly depend on its productivity and economic benefits for farmers. In a recent research Monti et al. (2006) found that the break-even yield of switchgrass, i.e. the yield threshold below which the cultivation of switchgrass is less economic than that of other crops, being from 11 to 15 Mg ha^{-1}. This result was encouraging because they were yields obtained under a wide range of climatic conditions (Monti et al., 2004; Sharma et al., 2003; Vogel et al., 2002; Sanderson et al., 1999). Nonetheless, yield prediction of switchgrass is still uncertain and this may discourage farmers from including this novel crop in conventional systems. Furthermore, biomass yield under similar environmental conditions was found to range from less than 5 to more than 25 Mg ha^{-1} (Monti et al., 2004; Elbersen et al., 2001; Pfeifer et al., 1990), even in plot experiments where plants are hand-harvested and soil characteristics are fairly constant. At farm level the range of biomass yield can increase even further due to the unpredictable spatial variation of soil properties (e.g. soil texture, nutrients, pH, slope etc.) or the difficulty of machines in recovering biomass (Vleeshouwers et al. 2000). Therefore, average biomass yield is expected to be very different on field or on plot scale (Vleeshouwers et al. 2000). To understand how biomass yield can potentially be increased, the variation in productivity across the field should be carefully estimated. Site specific soil characteristics associated with biomass yield should also be known so that areas of low productivity can be characterized. In general, farmers measure the average yield but without taking yield and intrinsic soil variations into account, thus practice is to treat the field uniformly. Stafford (1993) recognized however, that this is not only inefficient in terms of cost, but it also has undesirable environmental impacts, as inputs are applied to areas not requiring them (e.g. herbicide in free weeds zones) or where the crop cannot make full use of them (e.g. where nutrients are naturally available). Understanding field spatial variation and the relationships with crop response may therefore substantially increase the input effectiveness, increase the average biomass yield, and provide economic and environmental benefits. This is the core of precision farming theory.

To the best of our knowledge there are no reports in literature of studies on switchgrass yield variation within a small field and its possible relationship with soil spatial variability. A lot of experiments aimed at assessing the influence of one or few agronomic factors on switchgrass yield (Heaton et al., 2004; Muir et al., 2001; Monti et al., 2001), but they generally referred to plot experiments. In the field however, many factors conjointly act and positive effects may somewhat hide the negative ones. Therefore, present research addressed: i) to estimate the spatial variation of switchgrass yield under mechanized field conditions; ii) to assess the spatial variation of soil properties; and iii) to produce thematic maps of yield and soil parameters using geo-statistical kriging approaches in order to find possible relationships between soil parameters and biomass yield.

2. Materials and methods

2.1. Experimental site

The experiment was located in Ozzano dell'Emilia (lat. 44° 25' N; long. 11° 28' E, 80 m a.s.l.), Po Valley area, in a hill-field of 4.8 ha, previously cropped to sugar beet. The field prevailed to the Northwest and South; field slope was from 2% to 10%. It was classified as Typical Calcaric Cambisols (FAO), loam, clay-loam and silty-clay-loam with a clear prevalence of clay-loam type

(USDA classification). Soil tillage was carried out according to conventional techniques used for grasses. For the main soil treatment a Rabe-Week disc-plough (30 cm deep) pulled by a tractor (186 kW) was used. Cultivation was performed with a 300-cm wide Howard–type rotary cultivator. Before plantation a dose of 44 kg ha^{-1} of P (triple super phosphate) was applied. The A horizon was 30 cm deep in the entire field. Switchgrass (variety Alamo) was sown on 3 May 2002 by a seed drill commonly used for wheat. At emergence the seedling density was 106±18 plants m^{-2} (20 cm row-spaced). Annual N fertilization (100 kg ha^{-1}, urea 46% N) was supplied 20 days after emergence. Weed control was carried out only in the establishment year using glyphosate (3 L ha^{-1}) before sowing and after emergence nicosulfuron (40 g ha^{-1}, divided in two applications). Field harvested area was measured using a GPS devise (GEKO 201, Garmin Ltd.).

2.2. Yield and soil measurements

In order to assess the yield variability, two post-winter harvests (2004 and 2005) were performed as following: cutting, windrowing then square baling. During the operations the position of each bale and the machine track were geo-referred using the GIS software Arcview3.2 (ESRI). Each bale and the relative harvesting area were measured. Harvesting area referring to one bale was calculated on the base of cutter-bar width and the distance between two succeeding bales. Hence, a large area represents a longer machine track to produce one bale or a low productive area. Dry matter yield was calculated by the ratio of each bale weight to its harvesting area. Therefore, the yield is the average value of each area. To perform semivariograms this value was located in the center of each area (centroid).

A total of 60 soil samples regularly distributed across the field were collected and geo-referred during the emergence in 2004. Sand (SC), silt (SiC), clay (CC), organic matter (OM), pH, available P (P) and total N content (N) were determined in the upper 0.3 m. Each soil sample was dried (60 °C for 24 hour) and grounded for texture and chemical analysis (<2 mm fraction). The texture was determined according to Bouyoucos densimeter method (Gee and Bauder, 1986); soil organic matter was determined via redox reaction as given by Walkley-Black method (Walkley, 1947); pH was measured by a potentiometer dissolving 10 g of dry soil in 100 ml of water. P was obtained as given by Olsen et al (1954), i.e. extracting P in a 0.5M $NaHCO_3$ solution at pH 8.5 and than measuring by colorimetry with ascorbic acid-ammonium molybdate reagent. Total N was determined according to Kjeldahl digestion method (Kjeldahl, 1883).

A total of 165 measurements of soil strength (SS) were taken in the upper 50 cm using a soil cone penetrometer (ASAE, 1999), with an average soil moisture content of 204 mg g^{-1}. Soil moisture content (SM) was evaluated during emergence in the upper 0.3 m (100 samples) by the time domain reflectometry (TDR100 probe, Spectrum Inc.). Parameters measurements were not collected in exactly in the same location.

The normal distribution was estimated on skewness base: for a skewness range between -1 and 1 data were considered normally distributed. All data were standardized by subtracting the mean to each value then dividing for standard deviation.

2.3. Spatial structure and map creation

To produce thematic maps of yield and soil characteristics, kriging method (Krige, 1984) was used. In brief, the kriging is an advanced interpolation procedure generating estimated surfaces via semivariograms, which represent and characterize the spatial variation set against the distance (lag) (Isasks and Srivastava, 1989).

The spatial structure of each variable has been defined from semivariogram parameters: nugget, sill (or total semivariance) and range. Nugget is the variance at distance zero and represents the experimental error; sill is the semivariance value at which the semivariogram reaches the upper bound after its initial increase. It is the maximum variance for this kind of semivariograms and represents the total (*a priori*) semivariance of the study area; range is the value (x axis) at which one variable becomes spatially independent, that is the lag-distance at which the semivariogram flattens. The nugget to sill ratio quantifies the importance of the random component and provides a quantitative estimation of the spatial dependence. According to Cambardella et al. (1994), nugget/sill ratios can be grouped into three classes: (i) < 25% which means strong spatial dependence; (ii) 25 – 75%, moderate spatial dependence; (iii) > 75% spatially independent or pure nugget (i.e. when slopes of semivariograms are close to zero).

Spatial variation has been characterized using different models (spherical, circular, etc.) fitting the semivariograms. Choice of the best fitting model was based on the lowest RMSE (Root Mean Square Error) and confirmed by a visual inspection. The lag-distance used was between 5 and 12 depending on the variable. Cross-validation and ordinary kriging have been applied to extrapolate the values of unsampled field parts. To build semivariograms and kriged surface maps an ArcView GIS script (Kriging interpolator 3.2) was used, which is a full implementation of the kriging commands in avenue language working in the Spatial Analyst extension (Boeringa, 2006).

IDW (Inverse Distance Weighted) interpolation method, which assumes that each point has a local influence that decreases with distance (Bonham-Carter, 1994), was also used to produce maps in order to have a comparison with the kriging method.

Iso-elevation curves were digitalized using a 5 m range to calculate field slope and aspects. Data were organized into classes and displayed in graduated gray scale increasing from white to black.

2.4. Evaluation of factors and yield relationships

Because the number and location for measuring the parameters were different, a specific dataset was extracted from each kriged map to understand the correlation between yield spatial variability and soil parameters. A triangular point array with a distance between points of 15 m (resulting in 247 points) was superimposed on each map. At each point the interpolated value of the kriged map was assigned using the summarizing zone tool of ArcView3.2. The linear correlation coefficients ($P \leq 0.05$) were calculated as given by Pearson's test.

3. Results

3.1. Descriptive statistic

Descriptive statistic is summarized in Table 1. Basing on skewness value, all variables were normally distributed. However, some comments may be helpful for discussion. The 28% of SS values, mostly located in the northern part of the field, exceeded the penetrometer threshold (2.2 MPa). The yield spatial variation was highly relevant in both the years (CV higher than 30%). Biomass yield ranged from 2.3 to 14.6 Mg ha^{-1} in 2004 and from 3.7 to 24.4 Mg ha^{-1} in 2005. Spatial variation was also remarkable for P and SC (CV equal to 27% and 19%, respectively).

3.2. Spatial distribution of yield and soil parameters

Spatial variation was characterized using spherical, circular and exponential models. Fig. 1 shows actual and fitted semivariograms for all parameters. Spherical model was the most used, as frequently occurs in geostatistics (Webster and Oliver, 2001). Exponential model was only used for SiC (Table 2), that approached sill value asymptotically. In this case range value was considered the lag distance at which the semivariogram reached 0.95 times its sill (Webster and Oliver, 2001). The semivariogram slope was positive in all the cases, which means that there was a spatial dependence of all parameters. The semivariance of Y04, Y05, SM, SC, OM and pH increased with distance to a constant value (sill). For the other parameters (SS, CC and N) the semivariance increased without reaching a maximum at relatively low lag distance, indicating that a strict range value could be identified outside the field size, or that the number of samples were too few to extrapolate the spatial dependence (Cambardella and Karlen, 1999). Despite this the spatial class for these parameters may be evaluated using the sill value at which the semivariogram starts to flatten or by visual interpretation of the nugget significance (Fig. 1c, g and m). All these parameters were considered to have between moderate and weak spatial dependent (Table 2). Y05 semivariogram (Fig. 1b) decreased from its maximum to a local minimum and then increased again. This form is known as hole effect and depends by the process repetition (Webster and Oliver, 2001). A circular model was fitted to this semivariogram as wave models were not among the options of the interpolation software used.

Based on nugget/sill ratio (Cambardella et al., 1994), the spatial dependence was weak (i.e. high nugget/sill) in Y04, Y05, P and N, strong in SC and moderate for the other variables. Y04, Y05 showed the smallest ranges, with semivariograms rapidly flattening, suggesting likely patchy distribution of these parameters.

Yield maps and soil parameters obtained by ordinary kriging are displayed in Fig. 2 and 3. Biomass yield changed considerably across the field with the lowest values in the Southwestern and Eastern parts (Fig. 2a). This pattern was confirmed in 2005 (Fig. 2b), though with an overall higher yield of the more mature plants (3 years old). The maps of soil parameters showed increasing or decreasing values in one or two principal directions, but according to the method proposed by Webster and Oliver (2001), these trends were insignificant. In contrast Y04, Y05 and SC (Fig. 2 and 3c) showed a more prevalent patchy distribution.

3.3. Relationship between yield and soil parameters

Correlation coefficients were similar using IDW or kriging method, therefore only the coefficient based on kriged maps will be presented later on (Table 3).

Biomass yield was significantly related to nearly all soil parameters. In particular it was positively related to N and P and negatively to SM and pH (Table 3). Biomass yield was also negatively related to SS and this may be due to a lower root development. In addition, the negative effect of SS was probably enhanced by the concurrent low presence of P and N (r=-0.71** and -0.62** respectively).

Significant correlations were also observed between soil parameters. For example, SS with P and N; SM with pH; OM with pH (Table 3), the latter likely due to the acidification effect of humic acids. A close relationship was also found between N and P (r=0.76); both parameters were more concentrated in the middle of the field (Fig. 3h, i) where the highest yields were also recorded.

4. Discussion

The wide yield range suggests that switchgrass is strongly affected by soil variability, and thus the average switchgrass production can be substantially lower than its potential. For example, it was shown that the potential harvestable biomass within the field was more than 20 Mg ha^{-1}, while less than 3 Mg ha^{-1} where harvested in several low-yielding areas. This research however gives no mechanistic explanation of the yield variation, something that depends on conjoint effects of several contrasting or additive factors, that could not be adequately investigated here. What is clearly shown in this research is that areas with the lowest biomass production (the bottom-left white area in Fig. 2) were also those characterized by low SC and high SiC, pH and SS, parameters that were all significantly related to the yield. Therefore, the use of an appropriate site-specific practice may be expected to substantially increase the average yield.

Recording the variation in fields of a similar size was the objective of several studies (López-Granados et al., 2005; López-Granados et al., 2002; Cambardella and Karlen, 1999; Mallarino et al., 1999); nonetheless, only in a few cases was the crop yield also measured and related to the soil parameters (Shahandeh et al., 2005; Vrindts et al., 2003; Stafford et al., 1996). Yield variation was considered very relevant in barley, ranging from 2 to 6 Mg ha^{-1} (Stafford et al., 1996), and winter wheat, ranging from 3 to 12 Mg ha^{-1} (Vrinds et al., 2003). The authors explained the variability in the case of barley was as affected by soil series, and by chemical components, particularly P in the case of wheat. In this research the considerable variation in biomass yield across the field was associated to a parallel variation of soil components. It was not completely clear how biomass yield could be positively related to SC, but it may be that being negatively related to pH (r=-0.79**), the latter increasing P (r=-0.24**), that SC then indirectly increased the yield (r=0.43**). However, the effect of available P on switchgrass yield is still debatable because contrasting effects of this element on switchgrass yield have been reported (Muir et al., 2001; Brejda, 2000; Jung et al., 1988).

Soil N on the other hand has been shown to be the main determinant of yield spatial variation in annual crops (Shahandeh et al., 2005; Cox et al., 2003; Machado et al., 2000). The positive effect of

N on switchgrass yield was confirmed in plot experiments (Reynold et al., 2000; Sanderson and Reed, 2000), but we are not aware of any study on the influence of N on a field-scale. The results of our study showed a possible positive effect of soil N reserve on biomass yield. However, it should be highlighted that we only determined total and not available N, therefore the correlation between yield and N may only be indicative and further research is needed.

Kriging methodology was useful in describing the spatial distribution pattern of variance which can only be roughly understood by a descriptive statistic. In fact, some parameters may change gradually across the field, while others may show a patchy distribution. This can only be partly revealed using means and / or standard deviation. In contrast, semivariograms enable assessment of spatial dependence, which is needed to calculate sampling interval and develop an accurate site-specific application scheme (López-Granados et al., 2002). An overall rule is to use sampling intervals equal to the half of the semivariogram range (Kerry and Oliver, 2003). Therefore, the feasibility of precision farming applications may increase with the degree of spatial dependence. In this research, some soil parameters such as SC and OM were determined to be strongly or moderately spatially dependent, whilst the yield showed a weak spatial dependence of approx. 80 m (Table 2). Of course, the most intrinsic soil features such as SC can not be readily managed. Intuitively, the easiest way to increase switchgrass yield, and at the same time enhance environmental and economical benefits, would be site-specific applications of fertilizer. The total N and P seemed weakly spatial dependent, thus additional samples, at smaller lag-distances, may be needed for them. Nonetheless, high sampling density could, in same cases, be uneconomic and exceed the cost of saved fertilizer (Birrel et al., 1996).

5. Conclusion

To date, only average switchgrass biomass yield has been measured when using mechanized systems. This research on yield spatial variation highlighted however, that switchgrass biomass yield may considerably vary, even within a small field (from 3 to more than 20 Mg ha^{-1}). Therefore, the average biomass yield could be much lower than its potential, and much could be done to increase switchgrass yield. Soil parameters varied greatly across the field and biomass yield was significantly related to nearly all of them. Site-specific applications could therefore be expected to improve the yield and returns for farmers. At the sampling level used the spatial dependence of some soil parameters cannot be unequivocally identified, and for those parameters further research is needed to define more reliable semivariograms.

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Table 1

Sample number (N), mean, minimum (Min) and maximum (Max) values, standard deviation (SD), variation coefficient (CV) and skewness (SK) of the measured parameters (see list of abbreviations for parameters specification).

	Y04 ($Mg\ ha^{-1}$)	Y05 ($Mg\ ha^{-1}$)	SS (MPa)	SM ($mg\ g^{-1}$)	SC (%)	SiC (%)	CC (%)	OM ($mg\ g^{-1}$)	pH	P ($mg\ kg^{-1}$)	N ($mg\ g^{-1}$)
N°	146	286	165	100	60	60	60	60	60	60	60
Mean	7.9	11.5	1.8	204	33.2	36.9	29.9	127	7.9	10	10
Min	2.3	3.7	1.1	188	13.8	26.0	23.6	83	7.4	5.8	8
Max	14.6	24.4	2.1	275	39.6	52.0	39.6	160	8.4	16.94	12
SD	2.4	3.5	0.3	32	6.3	5.1	3.4	19	0.2	23	1
CV	30.4	30.7	14.5	16	19.1	13.7	10.4	15	3.0	27	11
SK	0.3	0.7	-0.3	-0.1	-1.0	0.7	0.2	-0.4	0.3	0.6	0.1

Table 2

Semivariogram models and spatial distribution parameters of standardized yields (Y04 and Y05, for the years 2004 and 2005, respectively) and soil parameters (see the list of abbreviations). RMSE is the root mean square error.

Parameters	Semivariogram model	Range (m)	r[1]	Spatial class[2]	RMSE
Y04	Spherical	100	76	W	0.14
Y05	Circular	60	77	W	0.13
SS	Circular	>300	26	S/M	0.11
SM	Spherical	160	57	M	0.13
SC	Spherical	220	16	S	0.33
SiC	Exponential	178	55	M	0.34
CC	Circular	>250	44	M	0.41
OM	Spherical	253	50	M	0.25
pH	Spherical	190	63	M	0.22
P	Spherical	192	80	W	0.18
N	Spherical	>250	77	W	0.37

[1] Random variation = nugget/sill%.

[2] Class of spatial dependence: S = strong; M = moderate; W =weak.

Table 3

Correlation coefficients (Pearson's test at $P \leq 0.05$) of biomass yield (Y04 and Y05 for year 2004 and 2005, respectively) and soil parameters (see list of abbreviations). Only the significant correlations are shown.

	Y05	SS	SM	SC	SiC	CC	OM	pH	P	N	Aspect	Slope
Y04	0.38	-0.37	-0.61	0.31	-0.43	-	-	-0.40	0.44	0.56	0.14	-0.22
Y05		-0.28	-0.27	0.13	-0.10	-	-	-0.43	0.45	0.34	-	-0.22
SS			-	0.19	-0.29	-0.45	0.40	-	-0.71	-0.62	0.33	0.28
SM				-0.39	0.54	0.24	-0.17	0.60	-0.13	-0.43	-0.30	0.15
SC					-0.89	-0.70	0.73	-0.79	-	-	-	-
SiC						0.68	-0.70	0.73	-	-	-0.20	-
CC							-0.76	0.63	0.38	0.27	-2.25	-
OM								-0.61	-	-	0.16	0.15
pH									-0.24	-0.39	-	0.10
P										0.76	-0.20	-0.22
N											-	-0.31
Aspect												0.24

Figure No: Fig. 1

Legend:

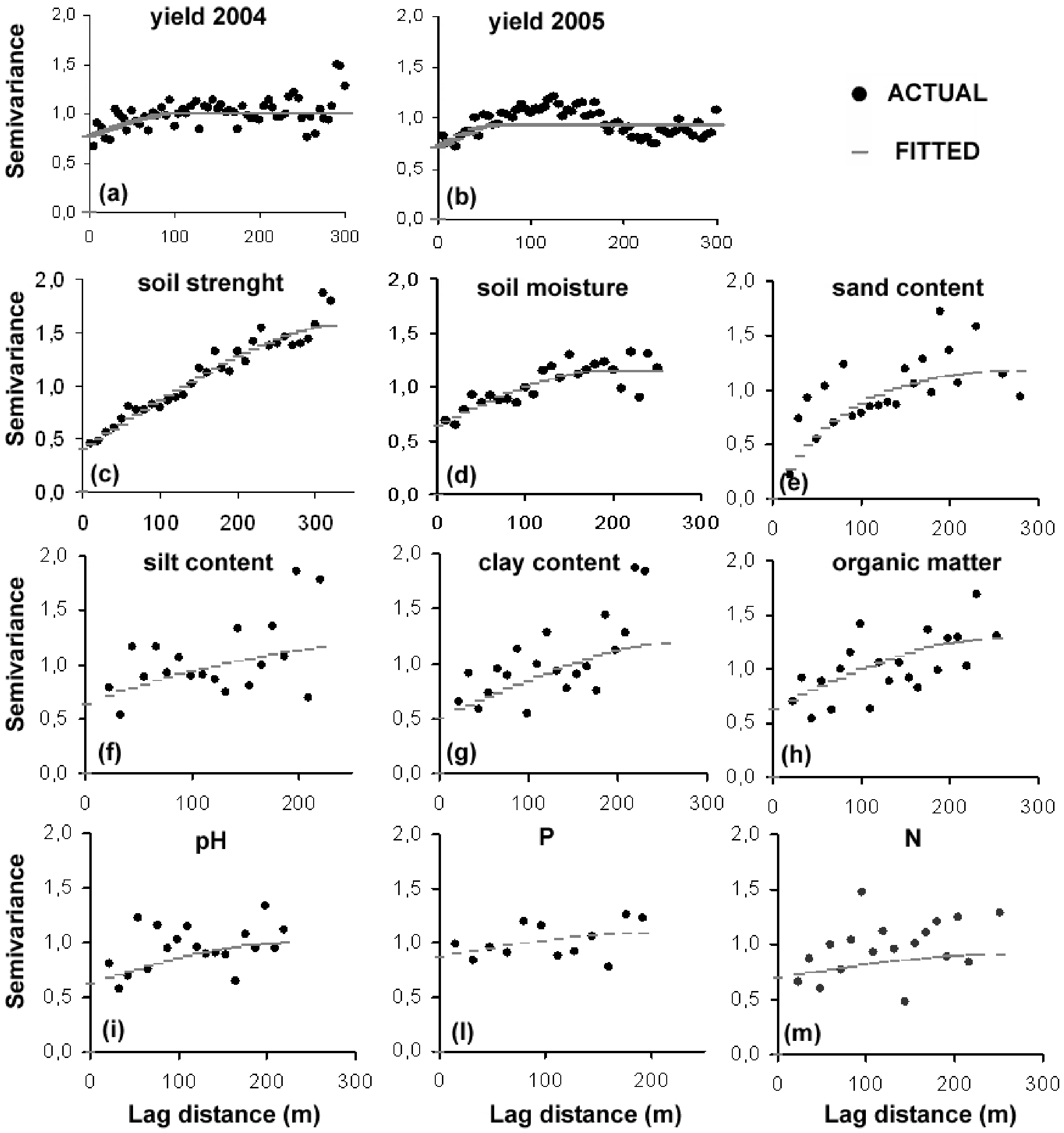

Fig. 1. Semivariograms showing actual semivariance of standardized data and fitted models for yield (a-b) and soil parameters (c-m).

Figure No: Fig. 2

Legend:

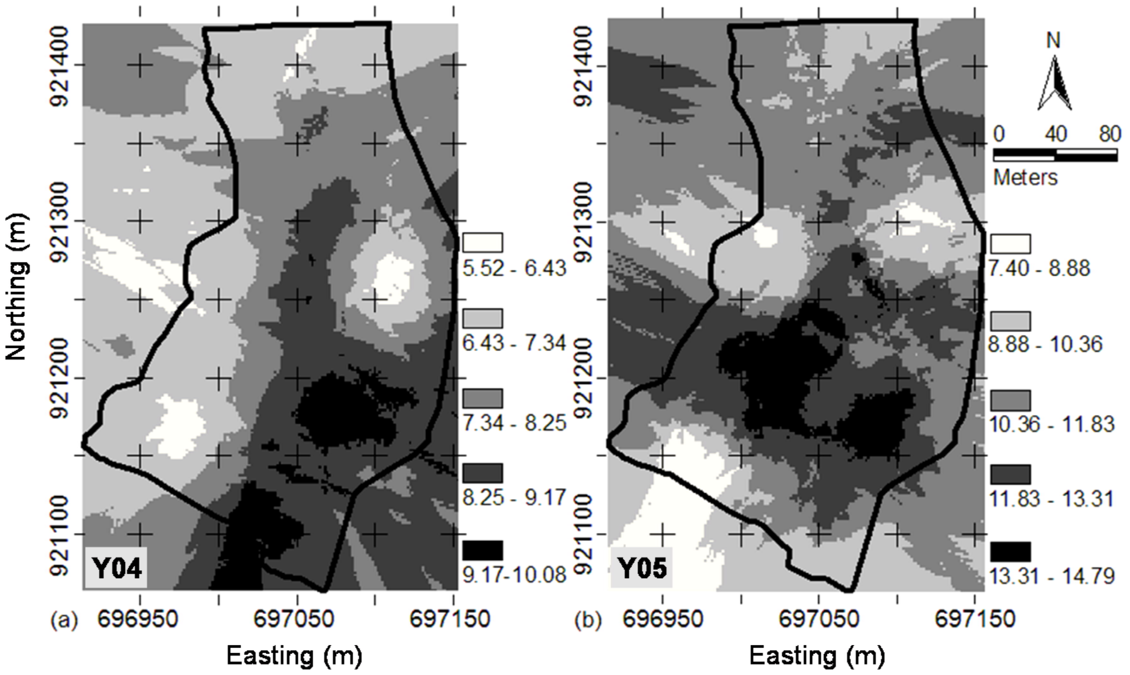

Fig. 2. Yield (Mg ha^{-1}) maps obtained by ordinary kriging: (a) 2004 (Y04), (b) 2005 (Y05). Maps show a patchy distribution.

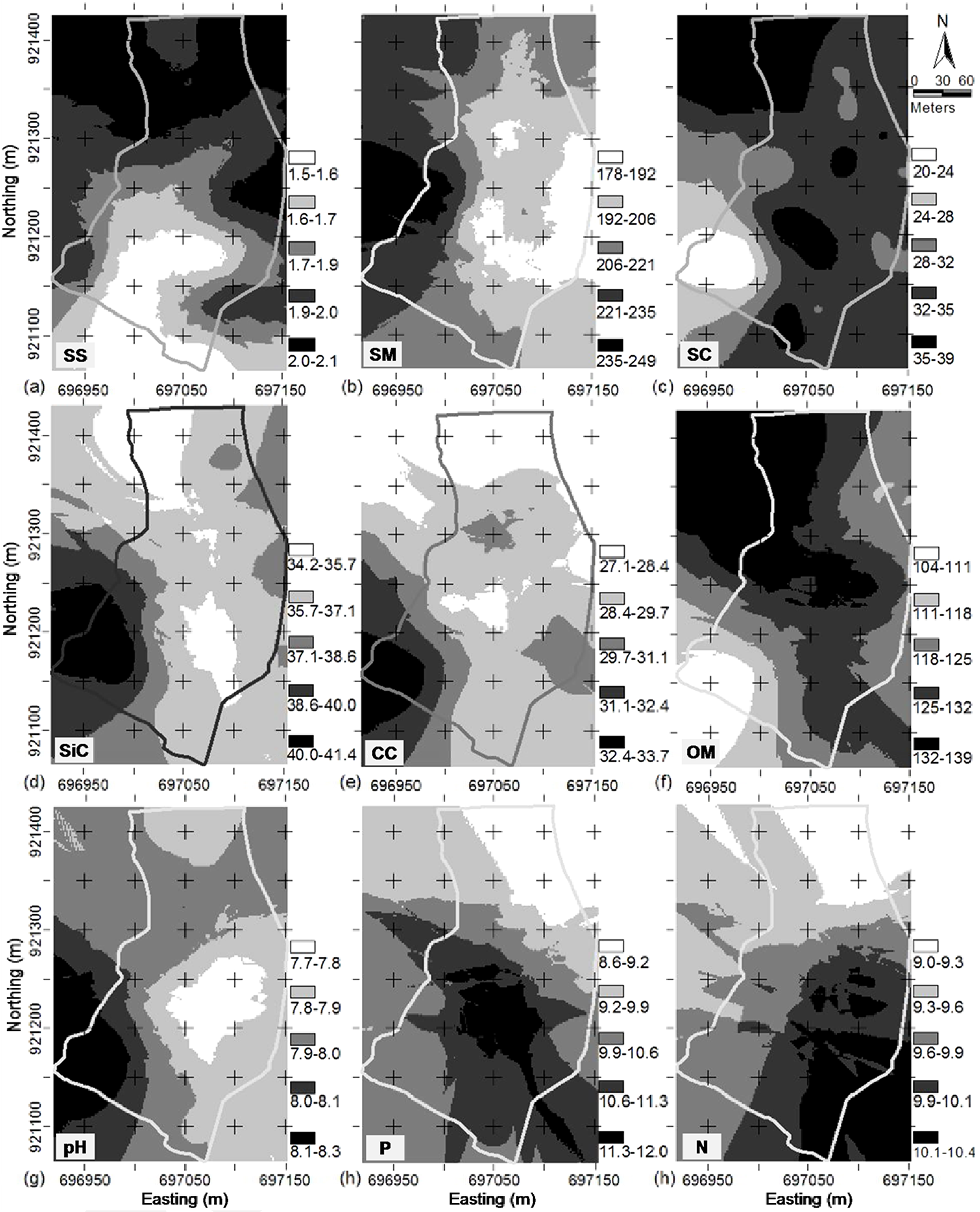

Fig. 3. Thematic maps of soil parameters: (a) soil strenght (MPa), (b) soil moisture (mg g^{-1}), (c) sand content (%), (d) silt content (%), (e) clay content (%), (f) soil organic matter (mg g^{-1}), (g) pH, (h) available P (mg kg^{-1}), (i) total N content (mg g^{-1}).

Figure No: Fig. 3

Legend: